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CONSTRUCTION AND SIMULATION OF
A GAS DYNAMIC LASER

by

Ronald Eugene Reedy

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A GAS DYNAMIC LASER

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Ronald Eugene Reedy

June 1970

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Construction and Simulation of a Gas Dynamic Laser

by

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Lieutenant (junior grade), United States Navy
B.S.E.E., United States Naval Academy, 1969

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis discusses the theory behind the gas dynamic laser. A computer program that solves the equations is included along with typical outputs. A description of a test apparatus is also presented with proof of laser action.

TABLE OF CONTENTS

I.	INTRODUCTION	11
II.	THEORETICAL DISCUSSION	12
III.	EXPERIMENTAL APPARATUS	21
IV.	RESULTS	25
	A. THEORETICAL	25
	B. EXPERIMENTAL	26
V.	CONCLUSION	27
	APPENDIX	28
	COMPUTER PROGRAM	29
	COMPUTER OUTPUT	50
	LIST OF REFERENCES	55
	INITIAL DISTRIBUTION LIST	56
	FORM DD 1473	57

TABLE OF CONTENTS

I.	INTRODUCTION	11
II.	THEORETICAL DISCUSSION	12
III.	EXPERIMENTAL APPARATUS	21
IV.	RESULTS	25
	A. THEORETICAL	25
	B. EXPERIMENTAL	26
V.	CONCLUSION	27
	APPENDIX	28
	COMPUTER PROGRAM	29
	COMPUTER OUTPUT	50
	LIST OF REFERENCES	55
	INITIAL DISTRIBUTION LIST	56
	FORM DD 1473	57

LIST OF ILLUSTRATIONS

Figure		Page
1	CO ₂ and N ₂ Energy Levels	37
2	Double-diaphragm Shock Tube	38
3	Regions of Interest in Shock Tube	39
4	Shock Tube Laser Diagram	40
5	Signal Conditioner	41
6	Biasing Circuit	42
7	End View of Shock Tube	43
8	Mirror Mount	44
9	Nozzle Assembly	45
10	Mirror Mount (disassembled)	46
11	Cutaway of Mirror Mount	47
12	Plexiglass Shield and Detector	48
13(a)	T.F.G. Output	49
13(b)	Endwall Pressure Gauge Output	49
14	Computer Output (test case)	50
15	Computer Output (actual case)	51
16	Population Inversion Comparisons	52
17	Population Inversion vs. Temperature	53
18	Detector Output	54

LIST OF TABLES

Table		Page
I	Description of Computer Variables	35
II	Correlation of Computer Variables to Basov Variables	36

TABLE OF SYMBOLS AND ABBREVIATIONS

Symbol	Description
a	Speed of sound
C_p	Specific Heat (constant pressure)
C_v	Specific Heat (constant volume)
$E(i)$	Energy in i^{th} Energy Level
M_e	Molecular Weight of an e Type Molecule
P	Pressure (atmospheres)
T	Temperature (absolute)
R	Universal Gas Constant
v	Velocity of Gas Particle
γ	Specific Heat Ratio
ρ	Density (grams/cm ³)

I. INTRODUCTION

The operation of any type of laser system depends on the production of a population inversion. Descriptions of the phenomena that take place in a laser may be found in [1] and [2]. There are several methods of producing a population inversion, one of which is by means of a gas dynamic process. The gas dynamic method usually incorporates a combination of rapid heating and rapid cooling of a gas.

In the rapid cooling phase, a gas that is initially at a high temperature and pressure is expanded by flow through a supersonic nozzle, which causes a sudden decrease in the temperature and pressure. The rapid drop in temperature is accompanied by a decrease in the population of the upper energy levels, each of which decays with a characteristic time constant. In certain gas mixtures the time constants are such that a lower energy level depopulates much more rapidly than a higher energy level. The result is a population inversion of these two states. The method has been successful in producing a laser output as shown by Kuehn and Monson [3]. In their experiment a large gas reservoir was heated and pressurized. The gas was then passed through a nozzle into an evacuated dump tank. Mirrors were placed in the sides of the nozzle to form the optical cavity.

It was the purpose of this thesis to build and test a gas dynamic laser utilizing a shock tube assembly to generate the initial high temperature conditions of reservoir gas, and to simulate the device on the digital computer according to the theory developed by Basov [4, 5].

II. THEORETICAL DISCUSSION

The fact that a gas dynamic laser is theoretically possible was established by Basov, et al. [4]. This work presented the requirements that must be met by a set of energy-level relaxation times if an inversion is to be established. The cases of rapid heating and rapid cooling were discussed. The ground states of a $\text{CO}_2\text{-N}_2$ mixture were found to satisfy the general requirements. Basov, et al. [5] examined this system in detail and offered a set of equations to describe the phenomenon. Part of the results of their work is a system of equations that describe vibrational relaxation. These equations are

$$\begin{aligned} v \frac{dE_1}{dx} = & 14Z_{\beta\beta} Q_{1,2} \left[-E_1 \left(2 \frac{E'_2 M_\beta}{\theta_2 R} + 1 \right) + \theta_1 \frac{R}{M_\beta} \left(\frac{E'_2 M_\beta}{\theta_2 R} \right)^2 \right] \\ & + 8Z_{\beta\beta} Q_{3,12} \left[-E_1 \left(\frac{E'_2 M_\beta}{\theta_2 R} \right) \left(\frac{E_3 M_\beta}{\theta_3 R} + 1 \right) e^{-\Delta} \right. \\ & \left. + \left(E_1 + \theta_1 \frac{R}{M_3} \right) \left(\frac{E'_2 M_\beta}{\theta_2 R} + 1 \right) \left(\frac{E_3 M_\beta}{\theta_3 R} \right) \right], \end{aligned} \quad (1)$$

$$\begin{aligned} v \frac{dE'_2}{dx} = & -7Z_{\beta\beta} Q_{1,2} \left[-E_1 \left(2 \frac{E'_2 M_\beta}{\theta_2 R} + 1 \right) + \theta_1 \frac{R}{M_\beta} \left(\frac{E'_2 M_\beta}{\theta_2 R} \right)^2 \right] \\ & + (Z_{\beta\beta} P_{2,\beta} + Z_{\beta\alpha} P_{2,\alpha}) \left[-E'_2 (1 - e^{-\Delta_2}) + \theta_2 \frac{R}{M_\beta} e^{-\Delta_2} \right] \\ & + 4Z_{\beta\beta} Q_{3,12} \left[-E'_2 \left(\frac{E_3 M_\beta}{\theta_3 R} + 1 \right) \left(\frac{E_1 M_\beta}{\theta_1 R} \right) e^{-\Delta} \right. \\ & \left. + \left(E'_2 + \theta_2 \frac{R}{M_\beta} \right) \left(\frac{E_3 M_\beta}{\theta_3 R} \right) \left(\frac{E_1 M_\beta}{\theta_1 R} + 1 \right) \right] \\ & + 78Z_{\beta\beta} Q_{3,2} \left[-\frac{\theta_2 R}{M_\beta} \left(\frac{E_3 M_\beta}{\theta_3 R} + 1 \right) \left(\frac{E'_2 M_\beta}{\theta_2 R} \right)^3 e^{-\Delta} \right. \\ & \left. + \theta_2 \frac{R}{M_\beta} \left(\frac{E'_2 M_\beta}{\theta_2 R} + 1 \right)^3 \left(\frac{E_3 M_\beta}{\theta_3 R} \right) \right], \end{aligned} \quad (2)$$

$$\begin{aligned}
v \frac{dE_3}{dx} = & 8Z_{\beta\beta} Q_{3,12} \left[-E_3 \left(\frac{E_1 M_{\beta}}{\theta_1 R} + 1 \right) \left(\frac{E'_2 M_{\beta}}{\theta_2 R} + 1 \right) \right. \\
& + e^{-\Delta} \left(E_3 + \frac{R}{M_{\beta}} \theta_3 \right) \left(\frac{E_1 M_{\beta}}{\theta_1 R} \right) \left(\frac{E'_2 M_{\beta}}{\theta_2 R} \right) \Big] \quad (3) \\
& + 52Z_{\beta\beta} Q_{3,2} \left[-E_3 \left(\frac{E'_2 M_{\beta}}{\theta_2 R} + 1 \right)^3 + e^{-\Delta} \left(E_3 + \frac{R}{M_{\beta}} \theta_3 \right) \left(\frac{E'_2 M_{\beta}}{\theta_2 R} \right)^3 \right] \\
& + \left(\frac{1-\gamma}{\gamma} \right) Z_{\alpha\beta} Q_{\alpha,3} \left[-E_3 e^{\Delta_{3\alpha}} \left(\frac{E_{\alpha} M_{\alpha}}{\theta_{\alpha} R} + 1 \right) \right. \\
& \left. + \left(E_3 + \frac{R}{M_{\beta}} \theta_3 \right) \left(\frac{E_{\alpha} M_{\alpha}}{\theta_{\alpha} R} \right) \right],
\end{aligned}$$

$$v \frac{dE_{\alpha}}{dx} = Z_{\alpha\beta} Q_{\alpha,3} \left[\left(\frac{E_3 M_{\beta}}{\theta_3 R} \right) \left(E_{\alpha} + \frac{R}{M_{\alpha}} \theta_{\alpha} \right) e^{\Delta_{3\alpha}} - E_{\alpha} \left(\frac{E_3 M_{\beta}}{\theta_3 R} + 1 \right) \right], \quad (4)$$

where

$$\begin{aligned}
Z_{\beta\beta}^{-1} &= 1.15 \cdot 10^{-11} (\gamma_P)^{-1} T^{1/2} \left(1 + \frac{190}{T} \right)^{-1}, \\
Z_{\beta\alpha}^{-1} &= 1.095 \cdot 10^{-11} [(1-\gamma)_P]^{-1} T^{1/2} \left(1 + \frac{132}{T} \right)^{-1}, \\
Z_{\alpha\beta}^{-1} &= 1.095 \cdot 10^{-11} (\gamma_P)^{-1} T^{1/2} \left(1 + \frac{132}{T} \right)^{-1}, \\
Q_{3,12} &= 0.124 T^{-1/6} \exp \left(-\frac{85.08}{T^{1/3}} + \frac{440}{T} \right), \\
Q_{3,2} &= 1.858 \cdot 10^{-2} T^{-1/6} \exp \left(-\frac{85.08}{T^{1/3}} + \frac{440}{T} \right), \\
Q_{1,2} &= 0.289 \cdot 10^{-6} T \exp \left(\frac{190}{T} \right), \\
P_{2,\beta} &= 6.47 \cdot 10^3 T^{-1/6} \exp \left(-\frac{131.055}{T^{1/3}} + \frac{670}{T} \right), \\
P_{2,\alpha} &= 1.82 \cdot 10^4 T^{-1/6} \exp \left(-\frac{120.165}{T^{1/3}} + \frac{612}{T} \right), \\
\Delta &= \frac{500}{T}, \Delta_2 = \frac{960}{T}, \Delta_{3\alpha} = \frac{30}{T} \\
Q_{\alpha,3} &= 0.516 \cdot 10^{-7} T \exp \left(\frac{132}{T} \right).
\end{aligned}$$

This gives a population inversion of

$$\frac{\Delta N}{N_0} = \frac{N_{[00^01]} - N_{[10^00]}}{N_0} = (\text{conc}) \left(\frac{Z}{Y} \right) (e_3 - e_1) (e_1 + 1)^{-2} (e'_2 + 1)^{-2}$$

where

conc $\equiv$ concentration of CO_2

$$Z = \frac{P}{P_0} \quad Y = \frac{T}{T_0} \quad \text{and} \quad e_i = \frac{E_i}{R\theta_i/M_i}.$$

In the equations, nitrogen is the " α " gas and carbon dioxide is the " β " gas. The Z_{ij} represent the number of collisions between a specific molecule of type i and any j type molecule. $P_{2\alpha}$ is the probability of resonant collision between a CO_2 and an N_2 molecule. $P_{2\beta}$ is the corresponding function for two CO_2 molecules. $Q_{n,m}$ are the probabilities of transition from one quantum state to another. The n and m correspond to the different energy levels shown in Figure 1. A listing of the (n,m) that goes with a given transition may be found in [5]. The θ_i are the characteristic temperatures of the corresponding levels, and are given by $\theta_i = \frac{h\nu_i}{k}$. Here, $h\nu_i$ is the energy of the given state above the ground state. The above relations give the rate of change of energy in specific energy levels of CO_2 and N_2 . E_1 through E_α represent the energies stored in the specific energy level. The initial values of E_1 through E_α are set by the relation $E_i = (R\theta_i/M_i)/(e^{\theta_i/T}-1)$ [5, 6].

A basic explanation of the origin of these equations starts by considering the change of population of some state of one particle as the particle undergoes collisions with another particle. The rate of change of population would be given by

$$\frac{dN_i}{dt} = Z_{e,p} \left[- \left(\sum_{\substack{n=1 \\ n \neq i}}^N P_{in} \right) N_i + \sum_{\substack{n=1 \\ n \neq i}}^N P_{ni} N_n \right]$$

where one is now considering an N-level system. P_{nm} is the probability that a particle will undergo a transition from the n^{th} energy level to the m^{th} energy level. (Basov uses p_{nm} to indicate a probability of transition due to resonant collisions and Q_{ij} to indicate a probability due to other than resonant collisions.) The first term on the right-hand side gives the depopulation of the i^{th} level. The second term introduces the repopulation of the i^{th} level. $Z_{e,p}$ is the number of collisions that an e type particle will undergo with a p type particle. Note that only transitions due to interaction with another particle are being considered at this point. Transitions that may be caused by other reasons (spontaneous, photon stimulated, etc.) are not included. These were assumed negligible.

In order to describe the population inversion process, one must know the transition probabilities (p_{nm}) and the collision rates $Z_{e,p}$. The actual calculations that must be carried through to obtain the p_{nm} will not be worked out here. Rather, an intuitive feel for the method used will be presented. One starts by writing Schroedinger's equation for the collision process [6]. This will result in a wave-function description of a particle that is under the influence of an intermolecular interaction potential. This interaction potential is a function of the distance between the involved particles.

The resulting wave functions can be written down as some combination of the wave functions of an isolated particle. The set of constants

that perform this transformation is directly related to the transition probabilities p_{nm} . The relationship between the elements of the set of constants and the transition probabilities is known, and is of sufficient simplicity as to allow calculation of the probabilities. The origin of the $Z_{e,p}$'s is discussed in [5] where they are derived from the kinetic theory of rigid molecules. The probabilities given by Basov are altered versions of the theoretical relationships so that the best experimental correlation results.

In order to form a closed system of equations that describes the gas dynamic process, one must describe the temperature, pressure and density as functions of time. This is necessary due to the dependence of the probability relationships on these parameters. The quasi one-dimensional flow equations form a set of independent equations that describe the above variables. One of the relationships is the equation of state:

$$P = \rho \frac{R}{M} T \quad (5)$$

where R is the universal gas constant and M is the molecular weight of the gas. If there is more than one gas, this equation can be separated into the partial pressure components. That is,

$$P_i = \rho_i \frac{R}{M_i} T.$$

Assuming steady-state flow, another relationship is the continuity equation, which is given by

$$\frac{d}{dx} (\rho av) = 0. \quad (6)$$

A third relationship is that for the conservation of momentum, as given by

$$\rho v \frac{dv}{dx} = - \frac{dp}{dx}. \quad (7)$$

Finally, there is the conservation of energy for adiabatic flow. This equation takes the form:

$$\frac{\rho_{\alpha}}{\rho} \left(\frac{7}{2} \frac{R}{M_{\alpha}} T + E_{\alpha} \right) + \frac{\rho_{\beta}}{\rho} \left(\frac{7}{2} \frac{R}{M_{\beta}} T + E_{\beta} \right) + \frac{1}{2} v^2 = H_0 \quad (8)$$

and in effect states that there is only a finite amount of energy that can be distributed among the different modes of energy storage.

These eight equations allow one to describe the relaxation phenomenon as exhibited by an adiabatically cooled gas. A digital computer program that solves the equations is shown in the Appendix.

Before describing the theory of the gas dynamic process, keeping the theory of the N_2 - CO_2 gas dynamic laser in mind, the N_2 - CO_2 molecular system will be discussed. The 10.6-micron N_2 - CO_2 molecular laser system inverts the population of certain of the molecular vibrational energy levels of the ground state of the CO_2 molecule. The vibrational energy levels are split by the molecular rotational energy. However, in the energy-level diagram, for clarity purposes, these rotational energy levels are not shown. The different vibrational modes of the ground state of the CO_2 and N_2 molecules are shown in Figure 1.

With reference to Figure 1, E_{α} is the lowest vibrational level of the N_2 atom. Since N_2 is diatomic, there is only one vibrational degree of freedom. This is a symmetrical stretching mode that can be visualized as similar to two balls that are attached by a spring.

(00^01) is the energy of the assymetrical stretching mode of the CO_2 molecule. This is the case of the two oxygen atoms moving in one direction while the carbon atom moves in the other direction.

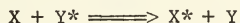
(01^10) is the bending mode energy. This is a degenerate state, as the molecule can bend in either of two perpendicular planes, the degeneracy being indicated by the superscript.

(10⁰0) is the energy of the symmetric stretching mode. This is the same as in the case of N₂, except that there is a "stationary" carbon atom between the vibrating oxygen atoms.

The above energy levels are simple harmonic oscillator states, and therefore the energy difference between the nth and (nth+1) energy levels is the same, regardless of the value of n. The nomenclature for the higher vibrational energy levels is the same as above. For example, the level (02⁰0) is the nondegenerate bending mode that has an energy of approximately twice the (01¹0) level. Note that although it is not shown, the (02⁰0) would be right below the (10⁰0) level.

There are other levels in the region shown by Figure 1, but the levels shown are those that enter into the strong 10.6-micron transition, and are the most important ones for the present purposes.

With the energy levels set forth, it is now necessary to explain several other phenomenon before the laser can be completely described. The first of these phenomenon is what is known as a collision of the second kind or a resonant collision. Basically the resonant collision is the interaction of two atoms, one of which is in an excited state. The other atom may be in any state. The result of the interaction is that the excited atom transfers its energy to the second atom, while returning itself to the ground state. This may be written schematically as [2]:



where the * indicates an atom in an excited state. It has been shown that the probability that the interaction will occur decreases as the energy gap between the energy level of atom Y and the closest available energy level of atom X increases. If the energy difference is greater

than 800 cm^{-1} , the collision will effectively not occur [7]. Although a proof will not be presented here, some insight can be gained by considering the fact that both the energy and the momentum of the two atoms must be conserved. This criterion is most readily fulfilled when there is little "internal" energy (i.e., electronic, vibrational, or rotational) that must be transformed into kinetic energy of translation of the atoms.

The next item that must be discussed is the N_2 energy-level diagram. As seen from Figure 1, for N_2 there is only one state of interest: the lowest vibrational level of the ground state. This state is a molecular level, and since N_2 has no net electric dipole moment, there can be no transitions directly to the ground state due to any electromagnetic interaction. The result is that for the N_2 molecule to return to the ground state from the vibrational levels it must undergo a collision with another particle (other molecules or the container walls). This is known as a metastable state, and is characterized by a long lifetime.

With the above information, the $\text{CO}_2\text{-N}_2$ molecular gas dynamic laser system can be described. Once the gas has been heated, populating the upper levels, it is then expanded by means of a supersonic nozzle. The excited N_2 molecules interact with the CO_2 molecules, and the two types of molecules undergo resonant collisions which serves to maintain the population of the 00^0_1 level of the CO_2 . The population of the other CO_2 energy levels depopulate rapidly as both levels (shown in Figure 1) are connected to the ground state by large transition probabilities. The large energy gap between these states and E_α prohibits repopulation due to resonant collisions. This creates a population inversion between the 00^0_1 and the 10^0_0 states. There are

other inversions, for example between the 00^0_1 and 02^0_0 levels, but the above inversion is the strongest, and gives the 10.6-micron transition. The lasing action may now occur.

There is one other characteristic of the N_2 - CO_2 laser system that should be pointed out. This is the fact that any impurities in the gases will cause a marked decrease in the output power. This is due to the resonant transfer of energy from the N_2 molecules to the impurity atoms, which robs energy that would have otherwise been pumped into the inversion.

Although the above theory does describe the same N_2 - CO_2 laser system, higher output powers can be obtained by the use of additives. In the case of a He- N_2 - CO_2 laser, a major factor in the population of the 00^0_1 level appears to be due to cascading effects from higher energy levels of both molecules [8, 12]. That is, there is resonant transfer of energy between the CO_2 and He at higher energy levels (collisions of the second kind at upper levels). The CO_2 molecules then spontaneously drop into the 00^0_1 level to set up the inversion.

III. EXPERIMENTAL APPARATUS

The previous section dealt with the theory behind the gas dynamic laser. The apparatus used to test the theory is shown in Figures 2 through 13. The shock-tube facility used had been previously built at the Naval Postgraduate School and it is discussed in detail by Penaranda [13].

Figure 2 shows a schematic of a double-diaphragm shock tube. The shock tube generates a shock wave by suddenly expanding a high-pressure gas into a low-pressure gas. The shock wave may be visualized as formed by the superposition of infinitesimal compression waves. The shock wave is accompanied by large gradients in temperature and pressure. The double-diaphragm arrangement was used because of the reproducibility of run conditions that it affords. In the double-diaphragm assembly, one drops half of the driver pressure across each diaphragm. The diaphragms (flat brass plates) are cut to withstand this pressure. However, when valve #1 is opened the entire driver pressure is felt across diaphragm #1 which has been cut to rupture well below this pressure. Therefore, the shock will always be originated by the same total driver pressure. This system eliminates the necessity that the diaphragms rupture at an exact pressure. The only requirement is that they rupture in the pressure range between the full driver pressure and one half that value.

Figure 3 shows the regions of interest for the case of a reflected shock wave. The shock wave is traveling into the driven gas (region 1) at a velocity S . The contact surface is propagating into the driven gas at a velocity C . This surface separates Region 2 from Region 3.

Regions 1 and 2 contain pure driven gas while Region 3 contains pure driver gas. That is, there is no mass flow across the contact surface. The array of lines in Region 4 represents the rarefaction wave, which is produced by the expansion of the driver gas. Region 4 is the driver gas at rest. Region 5 contains pure driven gas after the shock has reflected from the end wall of the shock tube. The conditions of the gas in Region 5 were used as the initial conditions for the experiment.

Analytical descriptions of the state of the gas in any of the regions may be obtained by means of the conservation of mass, momentum and energy equations in conjunction with the adiabatic gas laws. This is done in (9) and (10). The results of interest to the present experiment are

$$\frac{P_5}{P_1} = \left[\frac{2\gamma M^2 - (\gamma-1)}{(\gamma+1)} \right] \left[\frac{(3\gamma-1) M^2 - 2(\gamma-1)}{(\gamma-1) M^2 + 2} \right] \quad \text{and}$$

$$\frac{T_5}{T_1} = \frac{[2(\gamma-1) M^2 + (3-\gamma)] [(3-\gamma-1) M^2 - 2(\gamma-1)]}{[(\gamma+1) M]^2},$$

where γ is c_p/c_v , a_1 is the speed of sound in Region 1 and M is the mach number of the shock wave. The conditions in Region 5 can be controlled by variation of M , P , and a_4/a_1 .

The remainder of the physical apparatus is shown in Figures 4 through 12. Figure 4 is a schematic of the entire setup. The three amplifiers shown serve to amplify the signals from the thin film gauges (T.F.G. in the diagram). The distance between T.F.G. #1 and #2 is 5 ft. 3 in. Therefore by recording when the shock passes each of the gauges, the actual shock speed can be determined. The schematic of the amplifiers is shown in Figure 5.

The biasing circuit for the detector is shown in Figure 6. The detector is biased at about 370 microamps and gives a signal of several

millivolts. The detector is gold-doped germanium with a bandpass of 1.0 to 10.6 microns. The time constant of the detector is 50 nanoseconds.

The "dump tank" serves as a reservoir for the gas after it has passed through the optical cavity formed by the mirrors. As will be seen in a latter portion of this section, the observation time is on the order of 2 milliseconds. The particle velocity will be supersonic after the gas expands through the nozzle. For a particle velocity of 4000 fps, the dump tank must be 4 feet long to avoid interference of the returning gas with that gas that is still expanding through the nozzle. The gas that reflects from the end wall of the dump tank will introduce a change in the conditions within the gain path. This change in the conditions marks the end of the test time. The dump tank can be seen in Figure 7. The fingerlike projection from the endwall is a safety release valve, which is set to release when the pressure exceeds 200 psi. This is well below the rated pressures of all components in the system and will therefore prevent any overpressures from building up.

The mirror and nozzle assembly can be seen separated in Figures 8 and 9. A mirror mount is shown disassembled in Figure 10. A cutaway view is shown in Figure 11. The head of the bolt (shown in Figure 10 with the mirror attached) is ground off so that the mirror surface is recessed 0.075 inch from the nozzle wall. This is to help preserve the mirrored surface. Original test runs were made with gold-coated glass mirrors (not recessed) and mirror surface deterioration was severe. In some places the gold was dislodged from the glass. The recessing of the mirrors alleviated this problem.

The mirror has a radius of curvature of 4.5 inch (2.25-inch focal length). The gain path with the mirrors recessed is 3.14 inches. The mirrors are 98% reflective at 10.6 microns.

The nozzle is a linear nozzle with a half angle of 30° . The throat is 2 millimeters high. The center of the mirrors are 1.0 inch down the nozzle from the throat. The inside of the nozzle is roughened in order to minimize internal reflections of spontaneously emitted photons.

The plexiglass shield shown in Figure 12 absorbs any stray radiation. The end wall is at 10° to the incident beam (which enters from the left of Figure 12). This will reflect 7% of the energy. The reflecting surface is an IRTRAN 2 crystal. The hole drilled in the plexiglass behind the IRTRAN is to isolate the IRTRAN from the load (that is from another piece of plexiglass that will absorb the transmitted beam). The two metallic bars on the far side serve as counter-balances to the detector (which is filled with liquid N_2 under operation). The white wire carries the signal while the black lead grounds the detector and Dewar flask.

Figure 13(a) shows the output of the thin film gauges of the shock tube for a test run (0.5 m sec/cm). The conditions were 600 psi N_2 driving 40 mm Hg. ARGON was the driven gas. The resulting mach speed was 4.0. An endwall pressure gauge was substituted for the nozzle and its output is shown in Figure 13(b) (0.5 m sec/cm). The flat region in the middle of the trace is the observation time for Region 5, and is found to be on the order of 2 m sec.

IV. RESULTS

A. THEORETICAL

Figures 14 through 18 show different outputs from the computer program. Figure 14 shows a comparison of the program solutions to the predictions by Basov, et al. [5]. The case considered was for an axially symmetric nozzle, with initial test conditions of 10 atmospheres and 1500° Kelvin. The two solutions were found to differ by no more than 3%.

Figure 15 shows a comparison of the linear nozzle as used in the experiment to the hyperbolic nozzle considered by Basov. It should be noted that the pressure drops faster in the hyperbolic nozzle. The effect that this has on the population inversion can be seen in Figure 16. The two larger curves show comparisons of the computer predictions to Basov's predictions for the hyperbolic nozzle. The smaller population inversion in the linear nozzle is caused by the higher pressure and temperature (as compared to the hyperbolic nozzle). Also, since the temperature decreases more slowly in the linear nozzle, the peak in the population inversion occurs farther down the nozzle.

Figure 17 shows the population inversion at the center of the optical cavity as a function of temperature. There is some optimum temperature for each initial pressure and CO₂ concentration. Below this temperature less energy is pumped into the upper levels. Higher temperatures increase the gas velocity through the nozzle. Since the characteristic relaxation times are effectively independent of temperature in this range, the population inversion peak occurs farther down

the nozzle than the center of the optical cavity. This causes a smaller inversion at the center of the optical cavity.

B. EXPERIMENTAL

Figure 18 shows the result of one of the initial tests. Time limitations precluded further experimentation. The setup used in this initial test for lasing action was a modification of that shown in Figure 4. The modified setup used only the dual-beam oscilloscope. The oscilloscope was triggered by the first thin-film gauge. The second and third gauges were fed into different (i.e., opposite polarity) differential inputs of one channel. This was the lower trace in Figure 18. The detector output was fed directly into the second channel. The positive jump in the lower trace at 3.8 msec is the difference of the outputs of the second and third thin-film gauges, and comes just prior to reflection of the shock wave off the endwall. At this time the detector output shows a negative step, which was caused by the lasing action. Two milliseconds later the conditions of the gas were upset and the observation time as described by the computer program was over. This is noted by a slight ripple in the upper trace at 6.0 msec. The large spikes are due to recreation of favorable conditions by internal shock reflections. Their large size is due to mixing of the helium driver gas. This was shown by the fact that the spikes disappeared (but not the original step) when N_2 was used as a driver gas.

V. CONCLUSIONS

From the reproducibility of the output from the detector, it was concluded that lasing action was taking place. However, insufficient data were taken to permit comparison of the actual laser output to the theoretically predicted value. The only indication that the theory correlates with the experiment is the fact that a population inversion was predicted for the test conditions that resulted in laser output.

Further work with the system, as shown in Figure 4, is necessary to supply the data required for full comparisons between the theory and experimental results. Further experimentation with the laser should supply insight into both the validity of the theory and into the shock reflection and gas mixing that caused the large output spikes.

APPENDIX

The eight equations given in Section I form the closed set necessary to describe the gas dynamic laser. The computer program at the end of this section solves these equations. Descriptions of the variables may be found in tables I and II. There are a few portions of the program that need clarification.

The factor (TT/TC) in statement 25 ensures that $T = TT$ during the first iteration. If $T \neq TT$, a divergent solution results. In some cases the solution may converge after several iterations. The error between T and TT is small and is due to round-off errors of the conversion factors used.

The factor (0.98) in the relation for CSQ (C^2) also ensures computational stability. That is, in order to compute dp/dx , one must divide by $(1-v^2/C^2)$. At $x = 0$ (at the throat), $v = c$, and one would therefore be dividing by zero. The factor 0.98 ensures that this situation does not occur. The resulting error is less than 1%.

The subroutines RKLDEQ and OSPLLOT may be found in the USNPGS System 360 program library. More information on them may be obtained there.


```
// EXEC,FORTCLG,REGION.G0=100K,TIME.G0=32
// FORT.SYSIN 05 *
```

```
THIS PROGRAM COMPUTES AND PRINTS THE POPULATION INVERSION CREATED
BY THE GAS DYNAMIC LASER AS DESCRIBED IN THE THESIS BY
R.C. REEDY
```

```
THE00010
```

```
IMPLICIT REAL*8 (A-H, O-Q, S-Z)
DIMENSION Y(5), F(5), A(50), V(50,5)
READ (5,10) DMN,CONC,ARGC,PIAM
WRITE (6,10) DMN,CONC,ARGC,PIAM
FORMAT (1X,1F3.1,1X,1F4.3,1X,1F3.2,1X,1F5.1)
PIX=PIAM
G=CONC*1.293*(1.-CONC)*1.404
```

```
10
```

```
CALCULATE THE INITIAL CONDITIONS OF THE GAS
```

```
P51=((2.*G*(DMN**2)-(G-1.))/(G+1.))*((3.*G-1.)*(DMN**2)-2.*
1(G-1.))/(G-1.)*(DMN**2)+2.)
T51=((2.*(G-1.)*(DMN**2)+(3.-G))*((3.*G-1.)*(DMN**2)-2.*
1(G-1.)))/(G-1.)*2*(DMN**2))
T3=T51*300.
T2=1500.
Q1=477./T5
Q=1570./T5
```

```
THE00110
```

```
CP*Q2=1.85*(3.5+(Q1)/DSINH(Q1))**2)
CP*Q2=2.93*(3.5+(Q)/DSINH(Q))**2)
G*Q2=CP*Q2/(CP*Q2-1.86)
G*Q2=CP*Q2/(CP*Q2-2.93)
CP=CONC*G*Q2*(1.-CONC)*Q2
G=CONC*G*Q2*(1.-CONC)*Q2
```

```
THE00220
THE00210
```

```
WRITE (6,11) G,C,CP
FORMAT (1X, G CP,3F10.4)
```

```
111
```

```
T1=T5*Q2/(G+1.)
PI=PIAM/750.
T5=T5/T1
P5=P5*PI
P5=Q2/40
P5=PI/PI
DEN1=PI/(T1*(1.-CONC)*2.93+1.86*CONC))
DEN1=DEN1*(P5/T5)
DEN1=DEN1*(2./(G+1.))*((1.-CONC)/(G-1.))
Y(1)=1340.*(1./(DEXP(1920./T1)-1.))
Y(2)=67C./(DEXP(960./T1)-1.)
```

```
THE00260
```

```
THE00250
THE00270
THE00280
THE00290
THE00300
```



```

Y(3)=2350./DEXP(3350./TT)-1.)
Y(4)=2340./DEXP(3350./TT)-1.)
Y(5)=P5*(2./G+1.)**((G/(G-1.))
QA=(1.-CONC)*(Y(5)/TT)*(.171)
CB=CONC*(Y(5)/TT)*(.760)
VT=(G*(Y(5)*1.013006)/(DA+DR))**.5
Y(6)=VT
TC=(C1*(1-(DA*2.93+DR*1.86))*(CP*T5*(DA+DB)-(.5/1.013006)
1*(DA+DR)*Y(5))**.5-DA*Y(4)-DR*(Y(1)+2.*Y(2)+Y(3)))
WRITE(6,88) TT,TC
FORMAT(IX,' ',2F13.1)
X=0.
H=1.0-OF
NT=0
K=0
M=1
J=5000
WRITE(6,15) DMN,CONC,ARGC,PIAM,T5,P5
15 FORMAT(IX,DMN,CONC,ARGC,PI,T5,P5,1F4.3
1,1X,1F3.2,3X,1F6.1,5X,1F8.2,5X,1F6.2)
WRITE(6,60) Y(1),Y(2),Y(3),Y(4),Y(5),Y(6),DA,DR,TT,X
25 T=(TT/TC)*(C1*(1-(DA*2.93+DR*1.86))*(CP*T5*(DA+DB)-
1(.5/1.013006)*(DA+DR)*Y(5))**.5-DA*Y(4)-DR*(Y(1)+2.*Y(2)+Y(3)))
DA=CONC*(Y(5)/TT)*(.760)
DB=CONC*(Y(5)/TT)*(.171)
DSO=(.58)*(G*(Y(5)*1.013006)/(DA+DB)
CALCULATE THE DIFFERENT PROBABILITIES
ZBB=((CONC)*Y(5)*(1.+190./TT)/(1.150-11)*(T**5))
ZBA=((1.-CONC)*Y(5)*(1.+132./TT)/(1.0950-11)*(T**5)
ZAB=((1.-CONC)*Y(5)*(1.+132./TT)/(1.0950-11)*(T**5)
Q31=(1.124*(1./T**((1./5.)))*(1./DEXP(85.08/T**((1./3.))-440./T))
Q32=(1.8880-2*(1./T**((1./6.)))*(1./DEXP(85.09/T**((1./3.))-440./T))
Q12=.2890-C7*DEXP(133./T)
QA=.5160-C7*DEXP(133./T)
P2=.6.47D03*(1./T**((1./5.)))*(1./DEXP(120.165/(T**((1./3.))-670./T))
P2A=1.82D04*(1./T**((1./5.)))*(1./DEXP(120.165/(T**((1./3.))-670./T))
CALCULATE THE POPULATION RATES
F(1)=(1./Y(5))*(12.*ZBB*Q12)*(-Y(1)*(Y(2)/335.
1+1.)+1340.*(Y(2)/670.))**.2)+(8.*ZBB*Q312)*((-Y(1)*
2(Y(2)/670.)*(Y(3)/2360.+1.)*(1./DEXP(500./T)))+
3(Y(1)+570.*Y(2)/670.+1.)*(Y(3)/2250.))
F(2)=(1./Y(6))*(1.)*(7.*ZBB*Q12)*((-Y(1)*(Y(2)/
1335.+1.)+1340.*(Y(2)/670.))**.2)+(ZBB*P2B+ZBA*P2A)*(-

```

CCC 30

CCC


```

1./(Y(1)/2360.+1.))**2)*((1./(Y(2)/7670.+1.))**2))*{(
2./(Y(3)/2360.+1.))**2)
WRITE (6,60) Y(1),Y(2),Y(3),Y(4),Y(5),Y(6),DA,DR,T,X,PI
CALL THE PLOTTING SCHEME. IF THERE IS A TIME OVERRUN,
THERE WILL BE NO PLOT. THE POPULATION INVERSION
IS PRINTED OUT, HOWEVER, AS THE PROGRAM EXECUTES
CALL OSPL0T (A,V,K,K,1,0)
STOP
END

```

THE01030

```

SUBROUTINE OSPL0T(X,Y,N,NDIM,NCUR,ISCALE,XL,XH,YL,YH)
DIMENSION XS(11),YS(11),X(11),Y(NDIM),NCUR
INTEGER *2 IGRID(101)
INTEGER *2 ICH4R(6)/' + ' * ' ' & ' ' = ' ' . ' ' , /
IF(ISCALE.EQ.1)GO TO 32
XMAX=-1.0E-20
XMIN=-XMAX
YMAX=XMAX
YMIN=-XMAX
DO 25 I=1,N
  X(I)=XMAX
  Y(I)=YMIN
  IF(X(I)).GT.XMAX)XMAX=X(I)
  IF(Y(I)).LT.YMIN)YMIN=Y(I)
25 CONTINUE
DO 31 I=1,N
  IF(X(I,J).GT.XMAX)YMAX=Y(I,J)
  IF(Y(I,J).LT.YMIN)YMIN=Y(I,J)
31 CONTINUE
GO TO 34
32 XMIN=XL
  XMAX=XH
  YMIN=YL
  YMAX=YH
34 IF(XR.EQ.0.0)XR=1.0E-20
  IF(YR.EQ.0.0)YR=1.0E-20
  XI=XMAX*XMIN
  YI=YMIN*YMAX
  IF(XI.LT.0.0)IXAX=100.0*(-XMIN)/XR+1.5
  IF(YI.LT.0.0)IYAX=64.0*YMAX/YR+1.5
  XINCR=XR/16.0
  YINCR=YR/16.0
  XS(1)=XMIN
  YS(1)=YMAX

```

OSPL 0470
OSPL 0400
OSPL 0510
OSPL 0420
OSPL 0430
OSPL 0440
OSPL 0450
OSPL 0460
OSPL 0470
OSPL 0480
OSPL 0490
OSPL 0700
OSPL 0710
OSPL 0720
OSPL 0730
OSPL 0740
OSPL 0750
OSPL 0760
OSPL 0770
OSPL 0780
OSPL 0790
OSPL 0800
OSPL 0810
OSPL 0820
OSPL 0830
OSPL 0840
OSPL 0850
OSPL 0860
OSPL 0870
OSPL 0880
OSPL 0890
OSPL 0900
OSPL 0910
OSPL 0920
OSPL 0930
OSPL 0940
OSPL 0950
OSPL 0960

CCCCC

CDEL 1070
 CDEL 1080
 CDEL 1090
 CDEL 1100
 CDEL 1110
 CDEL 1120
 CDEL 1130
 CDEL 1140
 CDEL 1150
 CDEL 1160
 CDEL 1170
 CDEL 1180
 CDEL 1190
 CDEL 1200
 CDEL 1210
 CDEL 1220
 CDEL 1230
 CDEL 1240
 CDEL 1250
 CDEL 1260
 CDEL 1270
 CDEL 1280
 CDEL 1290
 CDEL 1300
 CDEL 1310
 CDEL 1320
 CDEL 1330
 CDEL 1340
 CDEL 1350
 CDEL 1360
 CDEL 1370
 CDEL 1380
 CDEL 1390
 CDEL 1400
 CDEL 1410
 CDEL 1420
 CDEL 1430
 CDEL 1440
 CDEL 1450
 CDEL 1460
 CDEL 1470
 CDEL 1480
 CDEL 1490
 CDEL 1500
 CDEL 1510
 CDEL 1520
 CDEL 1530
 CDEL 1540
 CDEL 1550
 CDEL 1560
 CDEL 1570
 CDEL 1580
 CDEL 1590
 CDEL 1600
 CDEL 1610
 CDEL 1620
 CDEL 1630
 CDEL 1640
 CDEL 1650
 CDEL 1660
 CDEL 1670

```

46  DO 46 I=2,11)+XINCR
47  DO 47 I=2,17)-YINCR
47  YS(I)=YS(I-1)-YINCR
    WRITE(6,10)(XS(I),I=1,11)
    II=1
    KK=0
    DO 145 LINE=1,65
    DO 101 J=1,101
    IGRID(J)=ICHAR(6)
    IF(YI-GE 0.0)GO TO 109
    IF(LINE-IXAX)109,104,109
    DO 105 J=1,101
    104  IGRID(J)=ICHAR(5)
    105  IGRID(J)=ICHAR(5)
    106  IF(XI-LT 0.0)IGRID(IYAX)=ICHAR(5)
    DO 125 J=1,NCUR
    DO 123 I=1,N
    IPTV=4.0*(YMAX-Y(I,J))/YR+1.5
    IF(IPTV.GT .65)IPTV=.65
    IF(IPTV.LT .1)IPTV=.1
    IF(IPTY-LINE)125,117,125
    117  IPTX=ICC.0*(X(I)-XMIN)/XR+1.5
    JC=MGID(J,4)
    IF(JC)119,118,119
    118  IGRID(IPTX)=ICHAR(4)
    GO TO 125
    119  IGRID(IPTX)=ICHAR(JC)
    125  CONTINUE
    IF(KK)133,133,134
    133  WRITE(6,20)YS(II), (IGRID(I),I=1,101),YS(II)
    II=II+1
    GO TO 135
    134  WRITE(6,20)(IGRID(I),I=1,101)
    135  KK=KK+1
    IF(KK-4)146,136,146
    136  KK=0
    146  CONTINUE
    WRITE(6,40)(XS(I),I=1,11)
    RETURN
    10  FORMAT(1H1,1PE13.2,1OE10.2/10X,1H*,20(5H+****),2H+*)
    20  FORMAT(1PE10.2,1H+,1O1A1,1H*,
    30  FORMAT(10X,1H*,1O1A1,1H*,
    40  FORMAT(10X,1H*,20(5H+****),2H+*/1PE16.2,1OE10.2)
    END
  
```


RKLC0010
RKLC0020
RKLC0030
RKLC0040
RKLC0050
RKLC0060
RKLC0070
RKLC0080
RKLC0090
RKLC0100
RKLC0110
RKLC0120
RKLC0130
RKLC0140
RKLC0150
RKLC0160
RKLC0170
RKLC0180
RKLC0190
RKLC0200
RKLC0210
RKLC0220
RKLC0230
RKLC0240
RKLC0250
RKLC0260
RKLC0270
RKLC0280
RKLC0290
RKLC0300
RKLC0310
RKLC0320
RKLC0330
RKLC0340
RKLC0350
RKLC0360

```

FUNCTION RKLDQ (N,Y,F,X,H,NT)
REAL*8 Y,F,X,H,0,H1,H2,H3,H6
DIMENSION Y(1), F(1), Q(25)
NT = N + 1
GO TO (1,2,3,4),NT
1 F1 = H
F2 = H1 * .5D0
H3 = H1 * 2.D0
H6 = H1 / 6.D0
DO 11 J = 1,N
Q(J) = 0.D0
A = .5D0
X = X + H2
GO TO 5
2 A = .2528932188134525
GO TO 5
3 A = 1.7071067811865475
GO TO 5
4 GO TO 5
41 Y(1) = Y(1) + H6 * F(1) - Q(1) / 3.D0
NT = 0
RKLDQ = 2.
GO TO 6
5 DO 51 L = 1,N
Y(L) = Y(L) + A * (H * F(L) - Q(L))
51 Q(L) = H3 * A * F(L) + (1.D0 - 3.D0 * A) * Q(L)
6 RETURN
END
//GO*FIC4F001 DD DCB=(RECFM=FA,LRECL=133,RLKSIZE=133)
//GO*SYSDD *
3.E.200.50 200.0

```


TABLE I

Variable	Physical Interpretation	Units
Y(1),Y(2),Y(3),Y(4)	Total energy in given level	cm^{-1}/gr
P5, P1, V(5)	Pressure	atmospheres
PIAM	Actual driven pressure	millimeters mercury
TT,T1,T5,T,TC	Temperatures	degrees Kelvin
Y(6), VT	Gas particle velocity	cm/sec
CSQ	Speed of sound squared	cm^2/sec^2
F(1),F(2),F(3),F(4)	Population rates	$\text{cm}^{-1}/\text{gr}/\text{sec}$
F(5)	Pressure rate of change	atm/sec
F(6)	Velocity rate of change	$\text{cm}/\text{sec}/\text{sec}$
PI	Normalized population inversion	dimensionless

TABLE II

Computer Variable	Basov Variable
Y(1),Y(2),Y(3),Y(4)	E_1, E_2', E_3, E_α
Y(5)	P
Y(6)	v
F(i)	F(i)
T5	T_o
P5	P_o
CONC	γ
Z_{ij}	Z_{ij}
Q_{ij}	Q_{ij}
P_{ij}	P_{ij}
PI	$\Delta N/N_o$

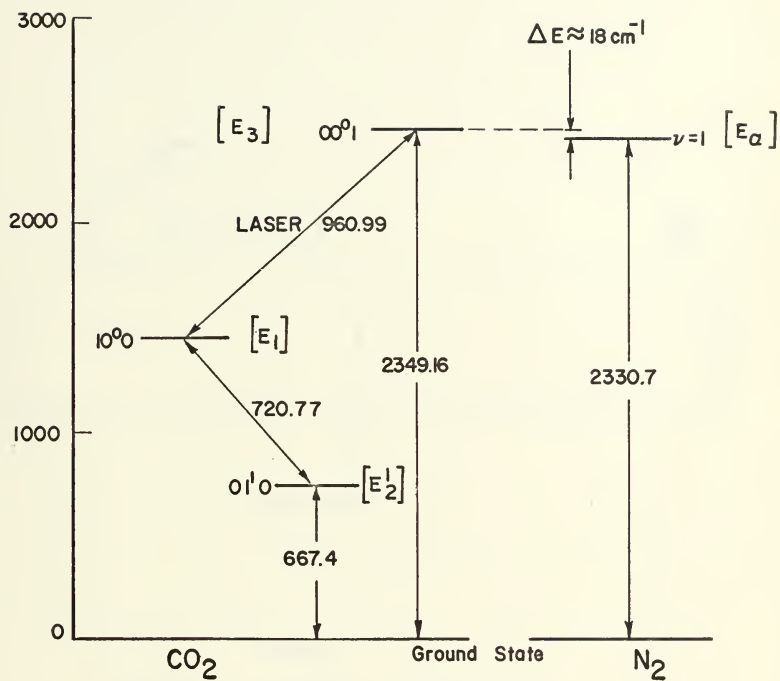


FIGURE 1
CO₂ AND N₂ ENERGY LEVELS (in cm⁻¹)

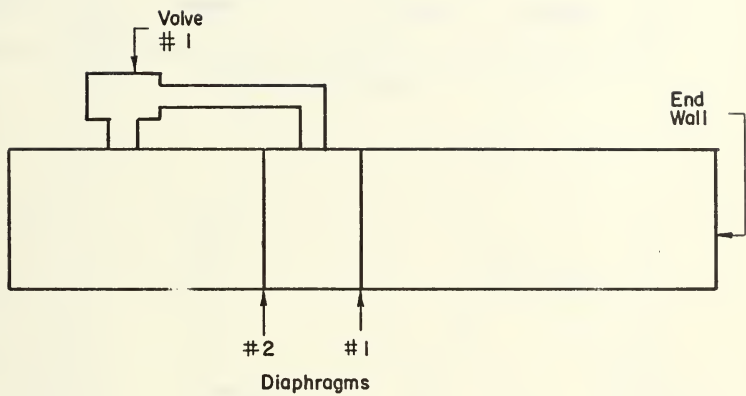


FIGURE 2.
DOUBLE DIAPHRAGM SHOCK TUBE.

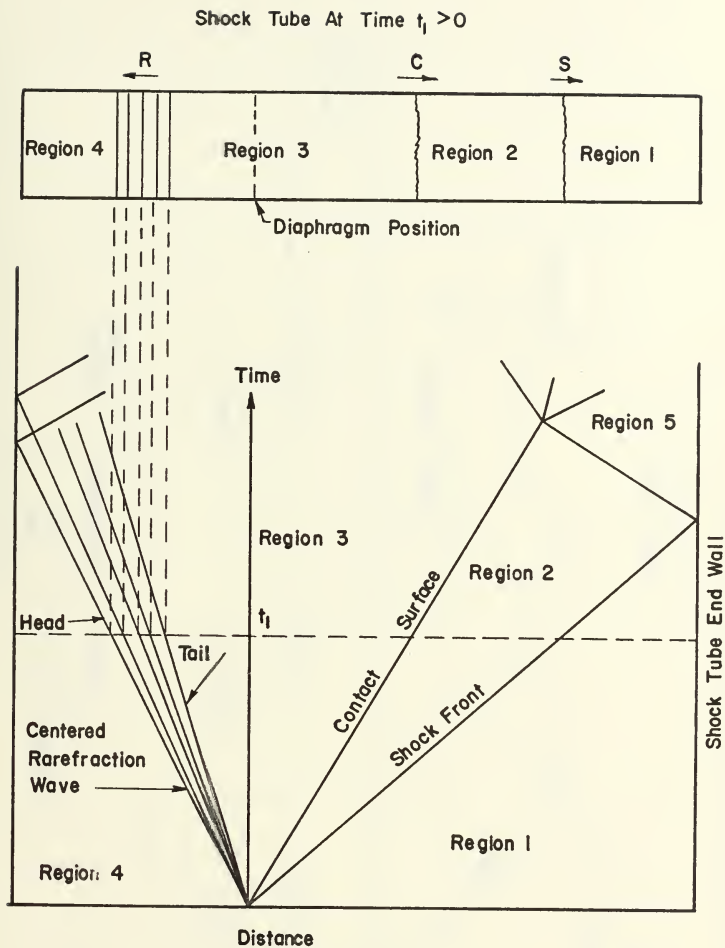
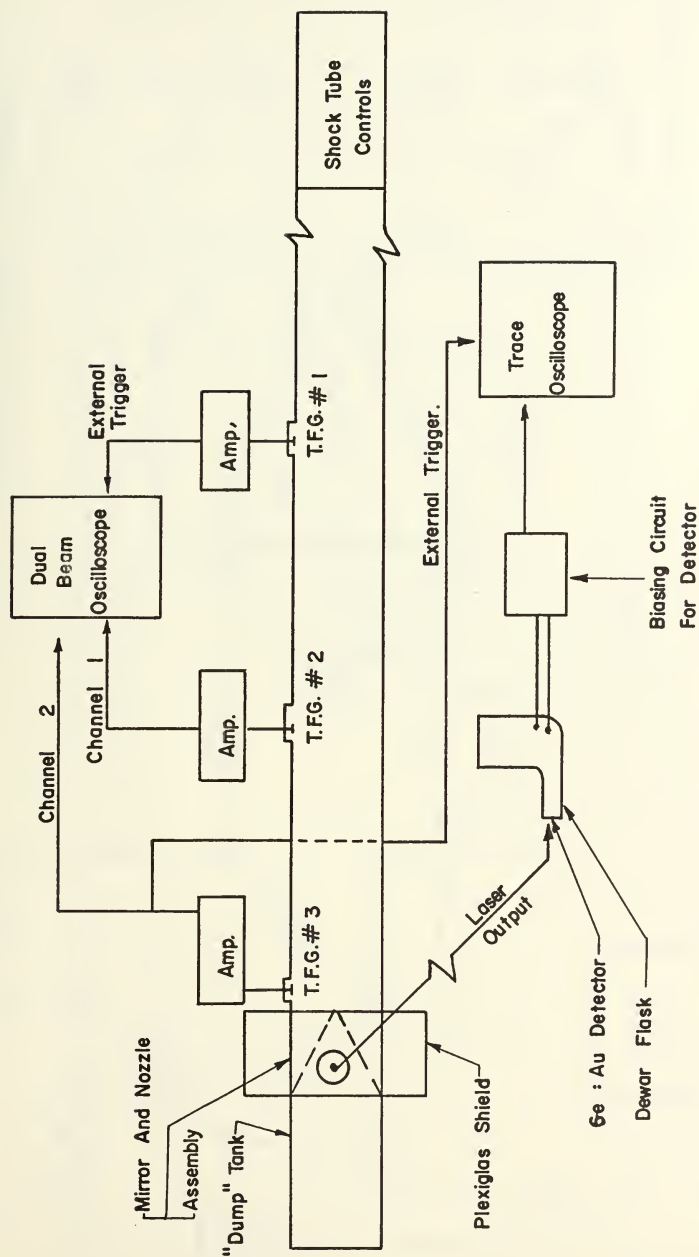


FIGURE 3

PLOT OF DISTANCE VS. TIME IN SHOCK
TUBE AFTER DIAPHRAGM IS BROKEN.



Note — The Dewar Flask Fits Into The Plexiglas Shield.

FIGURE 4
SHOCK TUBE LASER DIAGRAM

SIGNAL-CONDITIONER SHOCK-TUBE-FACILITY



THIN FILM
GAGE

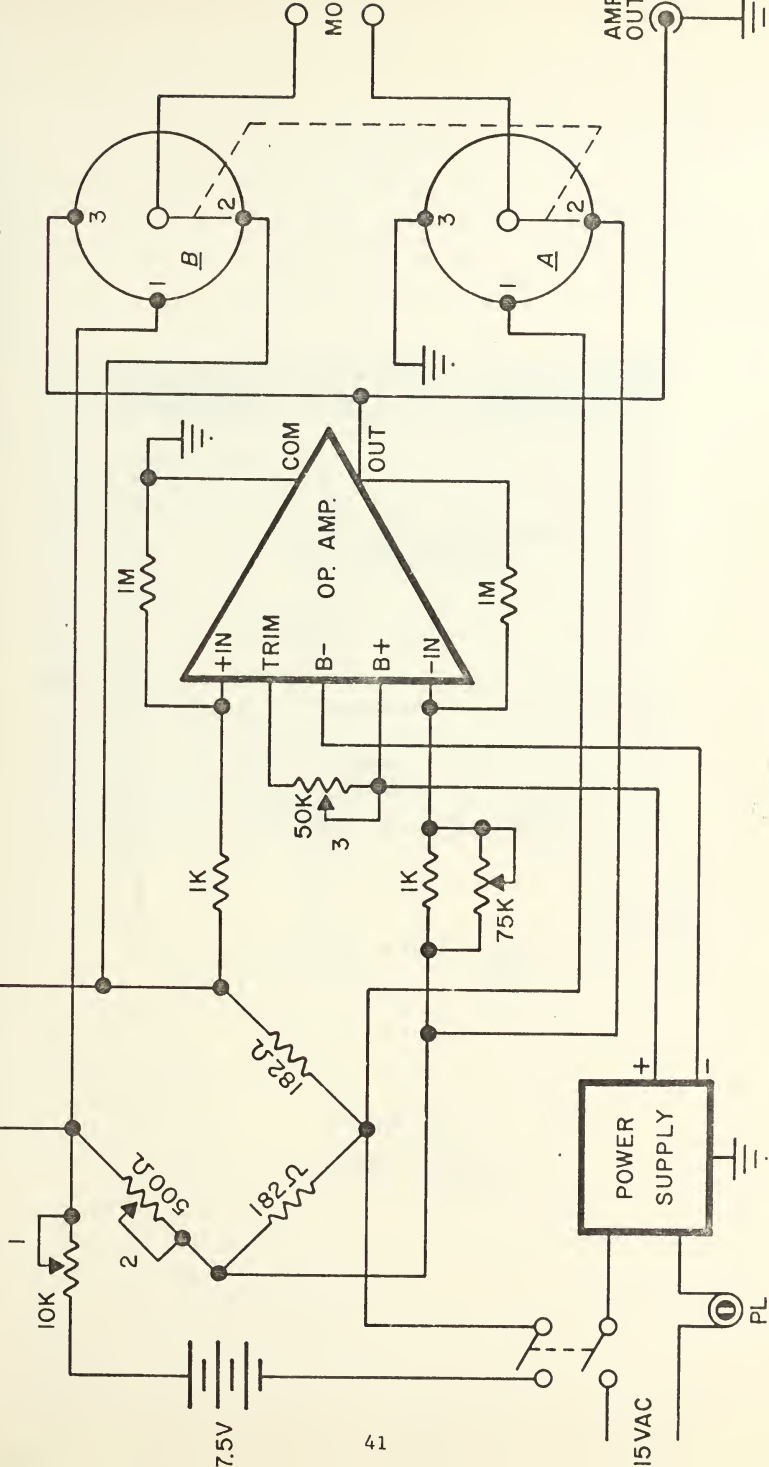


FIGURE 5

ADJUST NULL BIAS WITH A VTVM BEFORE
CONNECTING OUTPUT TO AMPLIFIER.

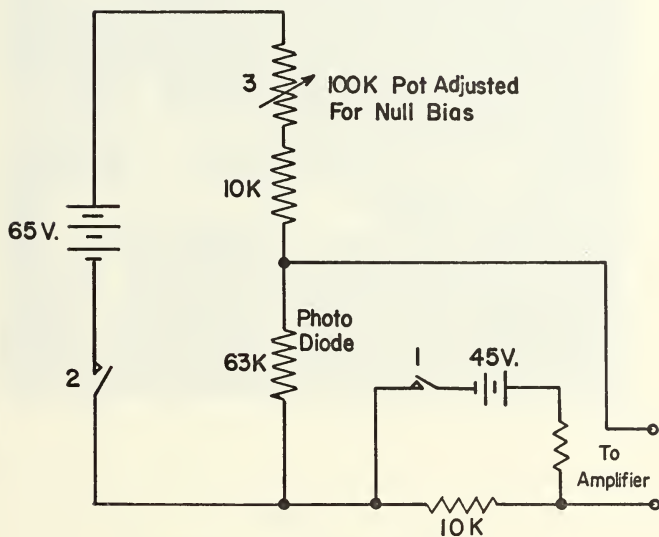


FIGURE 6
BIASING . CIRCUIT

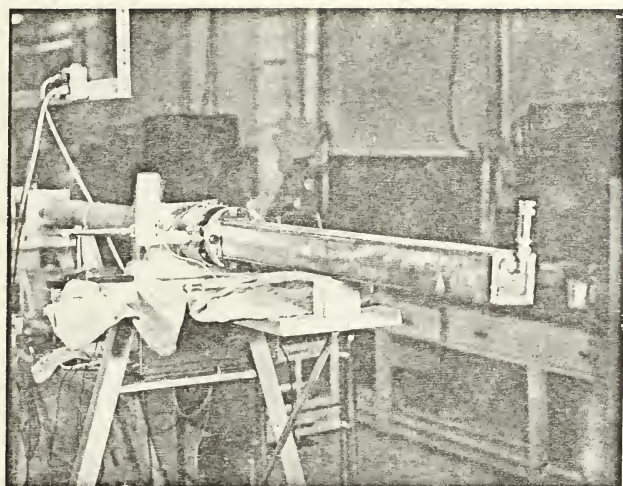


FIGURE 7.
END VIEW OF SHOCK TUBE

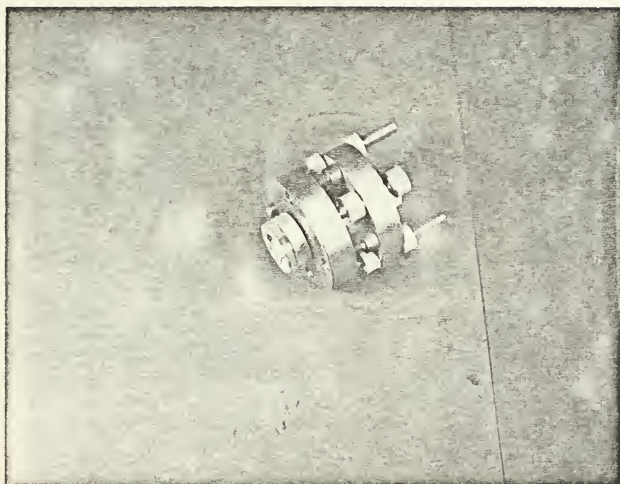


FIGURE 8
MIRROR MOUNT

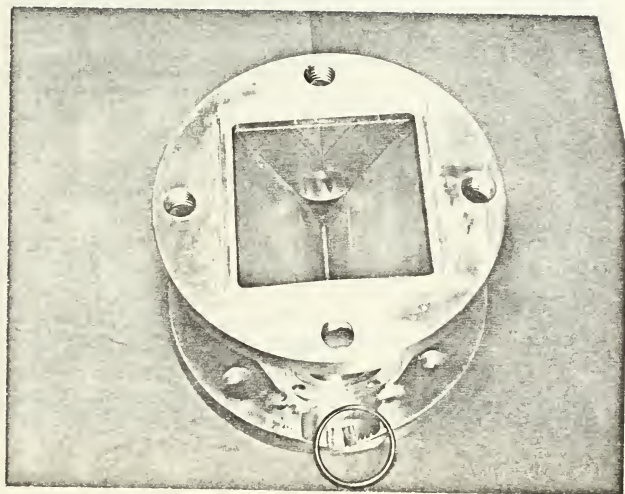


FIGURE 9
NOZZLE ASSEMBLY

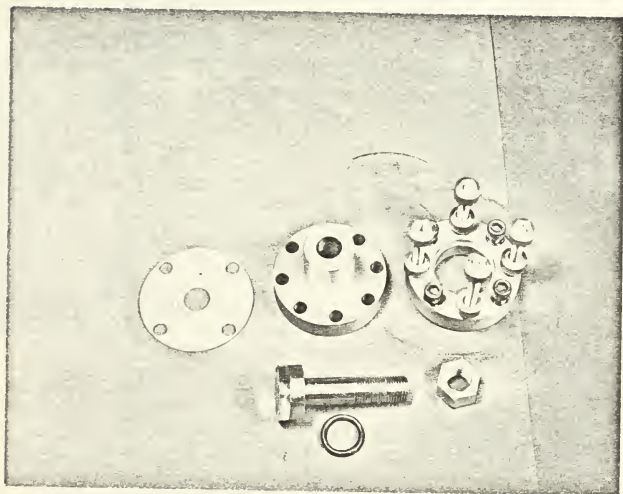


FIGURE 10
MIRROR MOUNT (DISASSEMBLED)

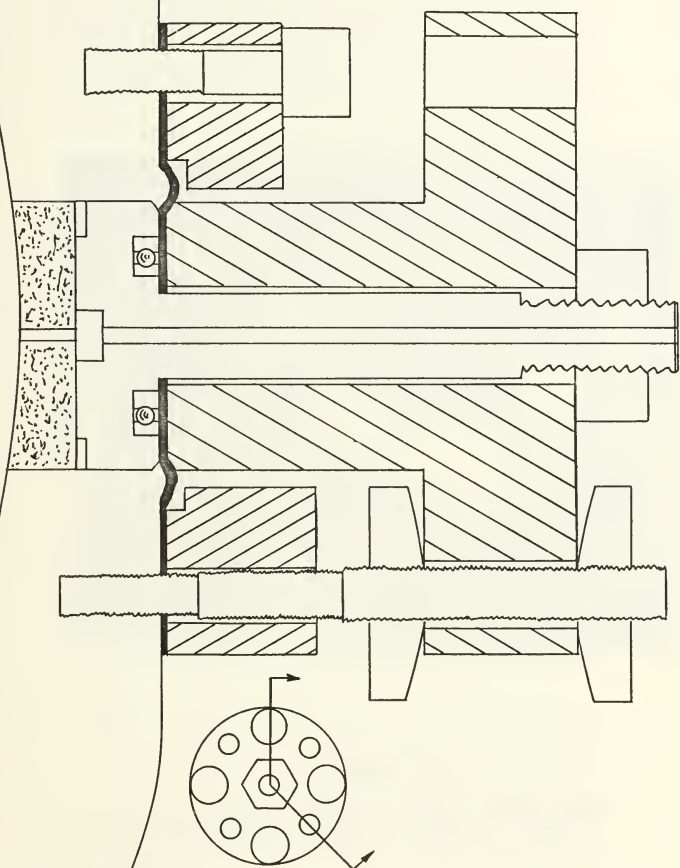


FIGURE II.
CUTAWAY OF MIRROR MOUNT.

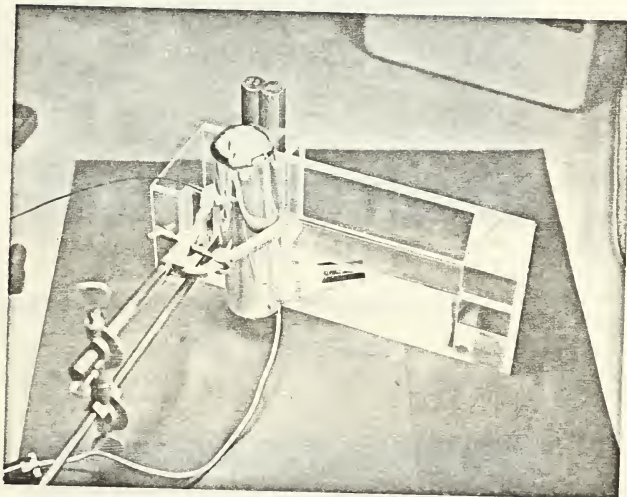


FIGURE 12
PLEXIGLAS SHIELD AND DETECTOR

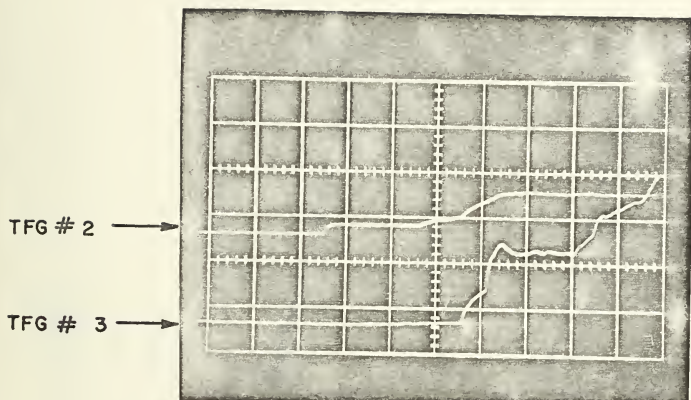


FIGURE 13(a)
OUTPUT OF T.F.G. FOR TEST RUN
(0.5 m.sec./ cm)

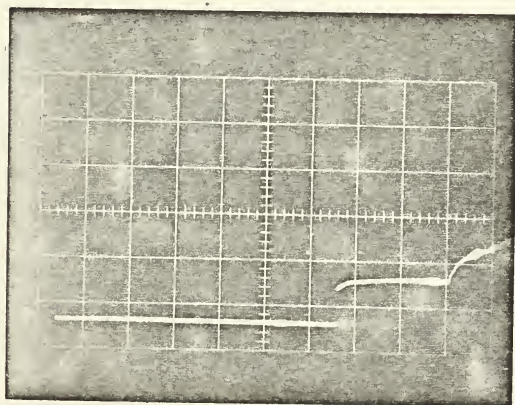


FIGURE 13(b)
OUTPUT OF ENDWALL PRESSURE GAUGE
(0.5 m sec./cm)

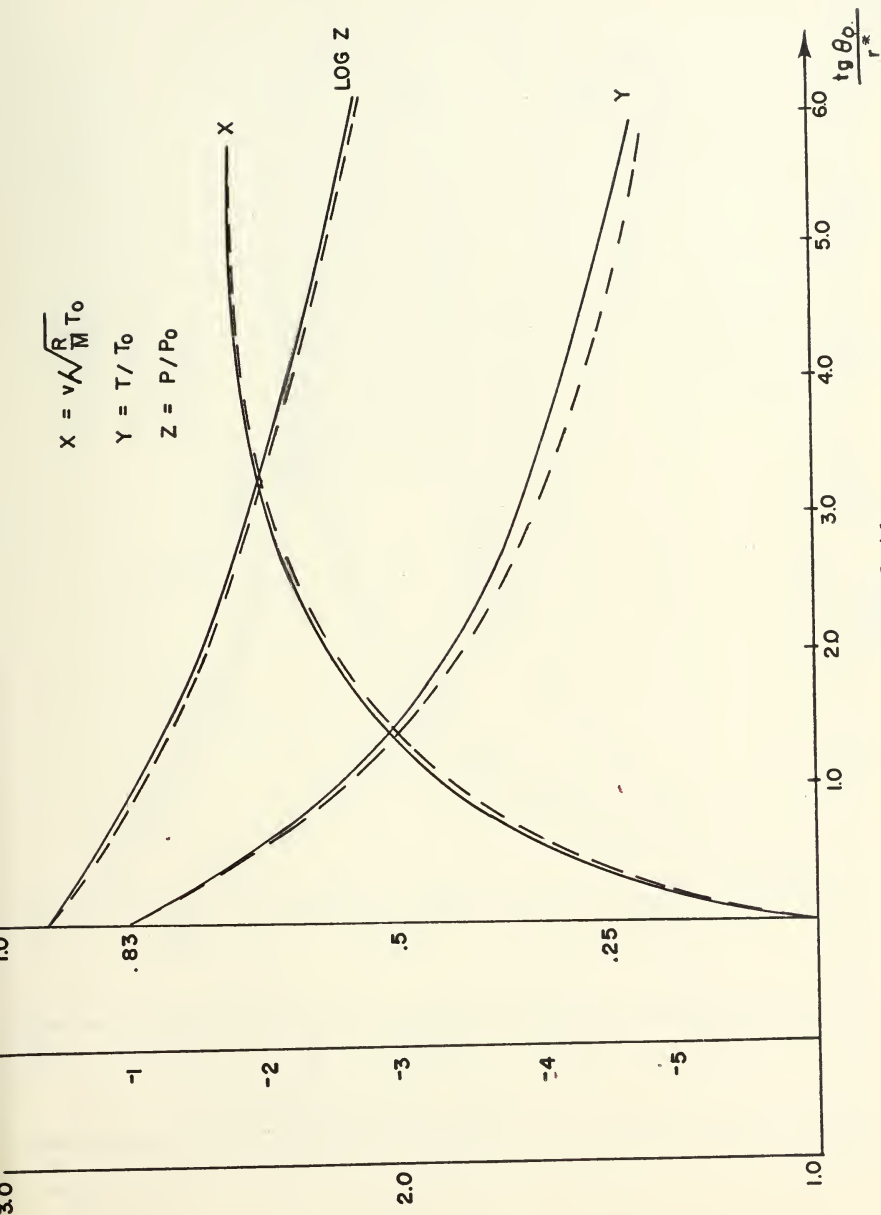


FIGURE 14
COMPUTER OUTPUT COMPARISON FOR IDENTICAL NOZZLE.

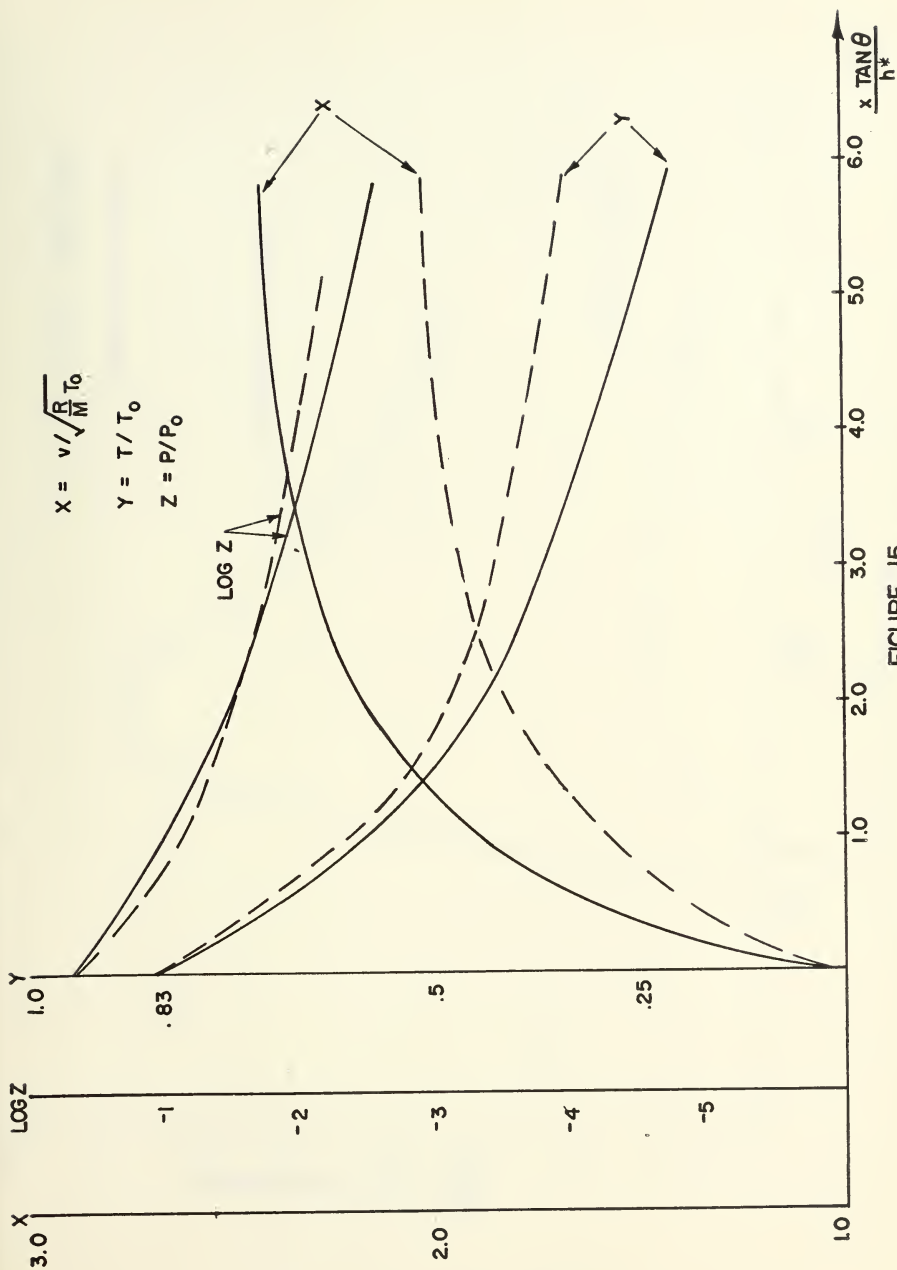


FIGURE 15
COMPUTER OUTPUT COMPARISON (LINEAR NOZZLE)

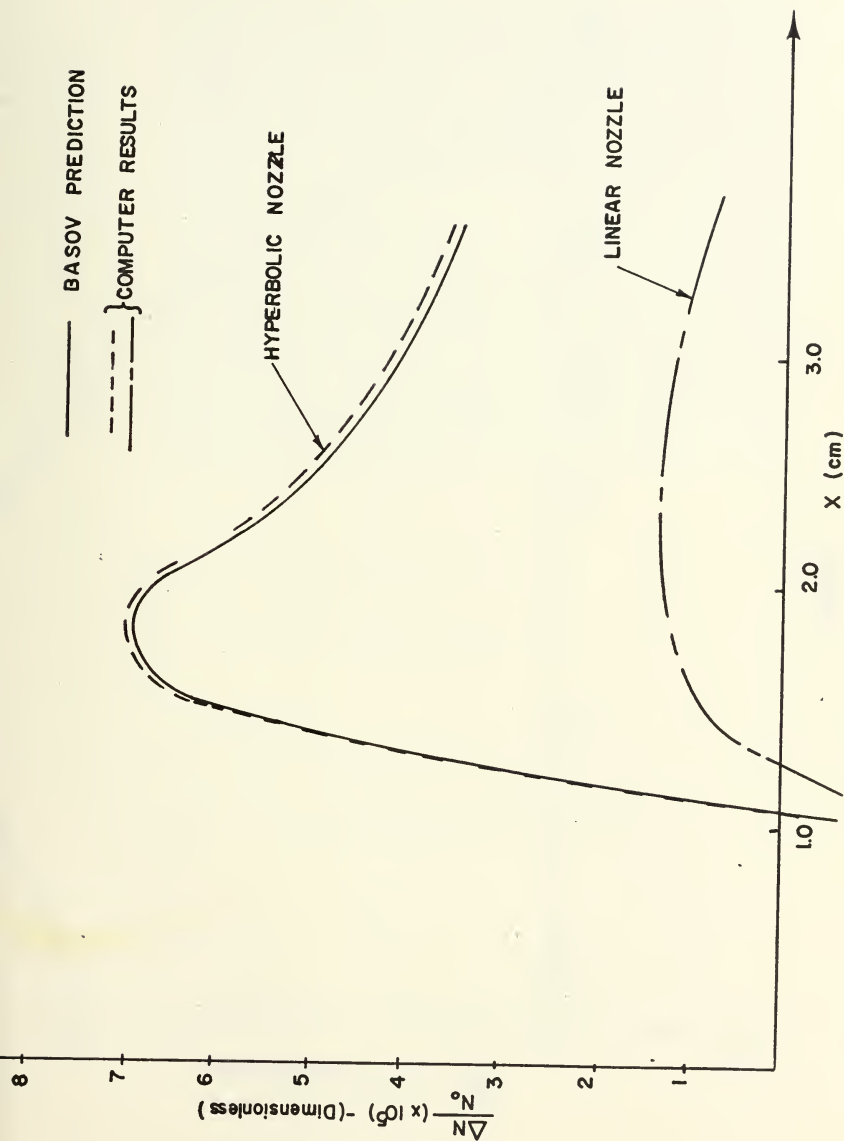


FIGURE 16
POPULATION INVERSION VS. DISTANCE DOWN NOZZLE

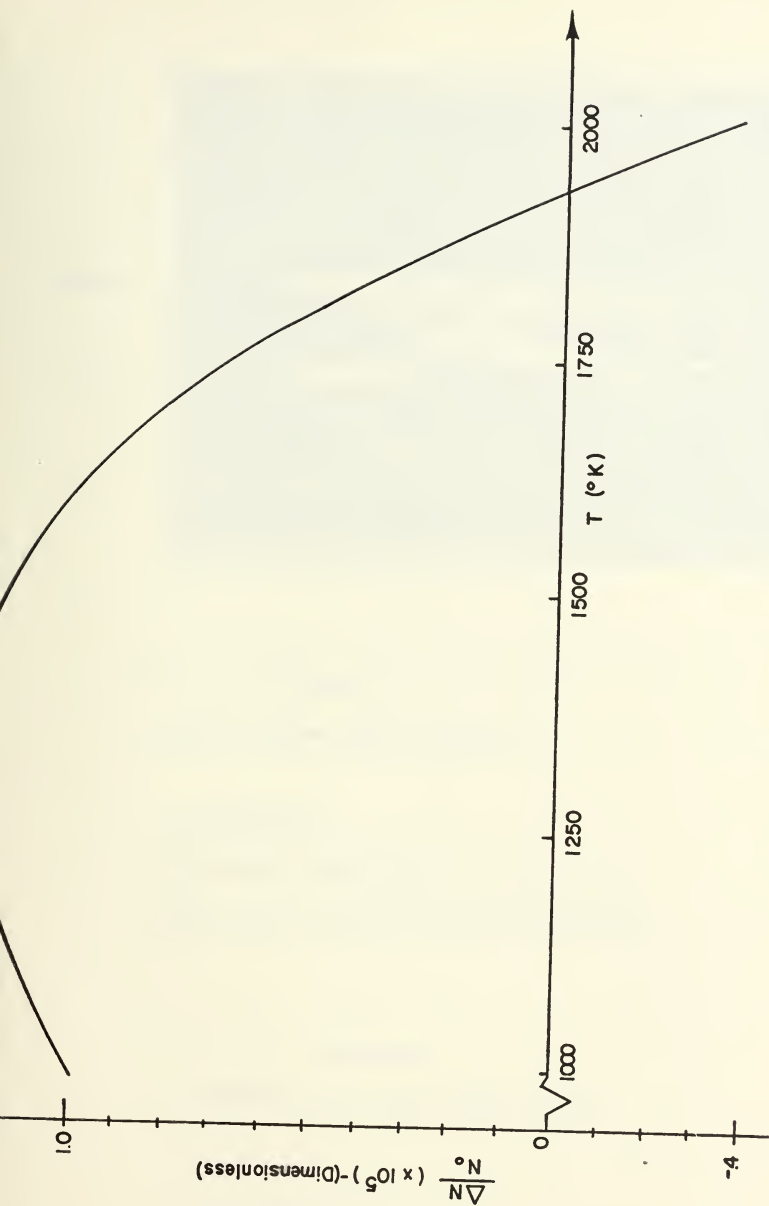
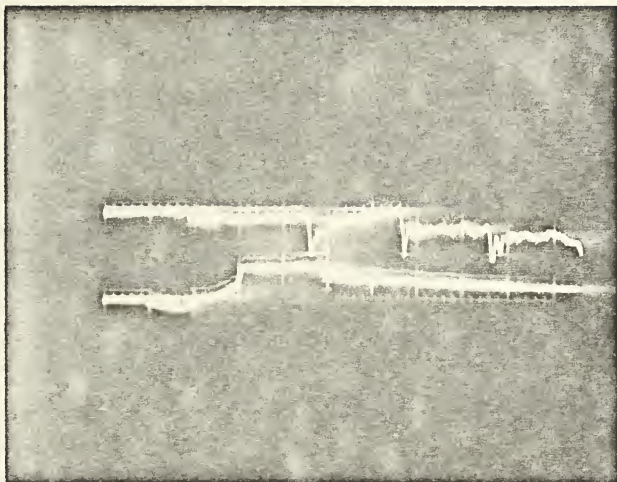


FIGURE 17
POPULATION INVERSION VS. TEMPERATURE AT
CAVITY CENTER (LINEAR NOZZLE)

Detector

T.F.G.



2 msec/cm

Lower and upper trace: 10 mv/cm

Run conditions:

Driven gas: 200 mm (Hg) of 20.7% CO_2 in N_2

Driver gas: 600 psi of 40% Argon in Helium

FIGURE 18

DETECTOR OUTPUT SHOWING LASER ACTION

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13. ABSTRACT

This thesis discusses the theory behind the gas dynamic laser.

A computer program that solves the equations is included along with typical outputs. A description of a test apparatus is also presented with proof of laser action.

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